# Tricuspid Valve Biomechanics: A Brief Review

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**Abstract** The mechanics of the tricuspid valve are poorly understood. Today's unsatisfying outcomes of tricuspid valve surgery, at least in part, may be due to this lack of knowledge. Therefore, the tricuspid valve in general, and its mechanics specifically, have recently received an increasing interest. This chapter briefly summarizes what we currently know about tricuspid valve mechanics. To this end, we separately review tricuspid leaflet mechanics, annular mechanics, and the chordae's mechanics. Moreover, we categorize our discussion by the experimental environment in which these tissues were studied: in vivo, in vitro, and in silico. Finally, we make suggestions as to which areas of tricuspid valve mechanics should receive additional attention from the biomechanics community.

**Keywords** Atrioventricular heart valve · Morphology · Microstructure · Constitutive behavior · Dynamics · Stress · Strain · Leaflet · Chordae tendineae · Annulus

## 1 Introduction

Once considered the "forgotten valve," the tricuspid valve has received increased attention over the past decade. This interest is largely driven by the high prevalence of tricuspid regurgitation, or leakage of the tricuspid valve. Also, current success rates of surgery for tricuspid regurgitation are far from optimal with as many as 30%

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of patients developing recurrent regurgitation 5 years after surgery [1, 2]. Being historically understudied, the hope is that a better understanding of tricuspid valve morphology, microstructure, constitutive behavior, and dynamics (referred to here as “biomechanics”) will ultimately lead to better clinical management of regurgitation through improved repair techniques and novel devices.

This brief review summarizes the relatively sparse data on tricuspid valve biomechanics. To this end, the chapter discusses these data separately for leaflets, annulus, and chordae tendineae and includes reports from in vivo, in vitro, and in silico studies.

## 2 Tricuspid Leaflets

### *2.1 Morphology and Nomenclature*

The tricuspid valve, as opposed to its left heart counterpart, the mitral valve, has three leaflets. These leaflets insert into the myocardium and connective tissue of the right atrioventricular junction, at the tricuspid annulus. Similar to the mitral valve, chordal attachments to the right ventricular endocardium prevent the tricuspid valve leaflets from prolapsing into the right atrium.

The leaflets are denoted as anterior (or superior), posterior (or inferior), and septal (or medial) according to their anatomical positions adjacent to the anterior right ventricular free wall, posterior right ventricular free wall, and the interventricular septum, respectively. In humans, the anterior leaflet is usually the largest leaflet, followed by the septal leaflet, and the posterior leaflet. The latter is frequently organized into two or more scallops, while the other two leaflets present with only one scallop (with few exceptions, [3, 4]). Additionally, there are interspecies differences. For example, in sheep only one scallop is usually observed in the posterior leaflet. Independent of species, the leaflets themselves are divided into a “rough” zone which extends from the free edge to the coaptation line, and a “clear” zone, which is identified by its translucency. A basal zone, between the clear zone and the annulus, is only found in the posterior leaflet in humans.

### *2.2 In Vivo Studies*

To the best of our knowledge there are no data available on the in vivo mechanics of the tricuspid leaflets. This paucity of data is likely due to the small thickness of the tricuspid leaflets (~300–700 μm), which prevents reliable identification with most imaging modalities especially in a dynamic environment such as the beating heart. Thus, there is an urgent need for investigation of the tricuspid leaflet mechanics using fiduciary marker techniques in the animal, for example.

## 2.3 In Vitro Studies

Khoiy et al. investigated the mechanics of the septal tricuspid leaflet in situ by suturing sonomicrometry crystals to the leaflet surface and pressurizing an explant porcine heart [5]. They found mean stretches across the leaflet at peak systolic pressure (30 mmHg) of 1.1 (maximum principal), 1.05 (circumferential), and 1.04 (radial). They concluded that the in vitro deformation of the septal tricuspid leaflet is similar to that of the in vivo anterior mitral leaflet [6]. In a similar setup, Pant et al. also studied microstructural changes in the tricuspid leaflets as a function of transvalvular pressure. To this end, they used a similar in vitro apparatus to Khoiy et al.'s previous study but replaced the pressurizing fluid with 0.5% glutaraldehyde. Subsequently they fixed the tricuspid leaflets in either an undeformed (unpressurized) configuration or a deformed (pressurized) configuration [7]. Using small angle light scattering, they then quantified the microstructural anisotropy of all tricuspid leaflets as a function of loading state. They concluded that transvalvular pressure results in strain-induced microstructural organization. In a similar study to Pant et al.'s, Hamed Alavi et al. [8] investigated the organization of the tricuspid valve leaflet matrix under uniaxial and biaxial loading using 2-Photon microscopy. They observed that the collagen fiber orientation in the relaxed state varies with depth and re-orients in response to uniaxial and biaxial loading in a depth-dependent and loading scenario-dependent manner.

In a right-heart in vitro simulator, Spinner et al. used dual camera photogrammetry to track visual marker points on the anterior and posterior leaflets of explant porcine hearts throughout the cardiac cycle [9]. In contrast to the studies by Khoiy et al., Spinner et al. isolated the tricuspid valves and fixed them to an artificial annulus rather than testing the tissue in situ. In this setup, they found that the anterior and posterior leaflets undergo large deformations throughout the cardiac cycle with mean maximum principal stretches of 1.22 and 1.53, respectively. Additionally, they tested the effect of (1) saddle shape (saddle vs. no saddle), (2) papillary muscle displacement (10 mm), and (3) annular dilation (100%) on leaflet stretches but found no significant differences between conditions. Given the relatively small sample number ($n = 8$) and large standard deviations, lack of significance may have been a result of type II error. However, if true these data would imply that the tricuspid annular saddle shape, in contrast to the mitral annular saddle shape, does not minimize leaflets stretches (and therefore stresses) questioning the saddle's teleological origin on the right side of the heart [10]. Noteworthy is the discrepancy between Spinner et al.'s findings and those of Khoiy et al. Spinner et al.'s stretches are significantly larger than those of Khoiy et al., which may be due to the differences in setups (isolated valve versus in situ) and the fact that they studied different leaflets.

Additionally, Pham et al. characterized the constitutive behavior of isolated human tricuspid valve leaflets. They used cadaveric tissue and executed a biaxial protocol to derive the stress-strain behavior of each leaflet. Additionally, they fit a Fung-type material model to their data [11]. They found that the tricuspid valve leaflets exhibit a highly nonlinear response and large degrees of anisotropy. By comparison to the leaflets of the other three heart valves, they additionally determined that the tricuspid leaflets are the most extensible and isotropic of all heart valve leaflets and that tricuspid leaflet extensibility decreases with age. Khoiy et al. also executed a biaxial protocol to investigate the constitutive behavior of isolated porcine tricuspid valve leaflets [12]. In their study, they confirm the large degrees of nonlinearity and anisotropy of the tricuspid valve leaflets reported above and found that the posterior leaflet is the most anisotropic of the three.

### *2.4 In Silico Studies*

We have been able to identify only two numerical studies on the mechanics of the tricuspid valve [13, 14]. Kamensky et al. used the tricuspid valve as an application for a novel contact algorithm. Thus, it is not a detailed report on tricuspid valve mechanics. Stevanella et al., on the other hand, performed detailed analyses of tricuspid valve mechanics. In Stevanella et al.'s study, due to a lack of matched data, the authors combined information from sonomicrometry studies on the ovine tricuspid annulus [15], tricuspid leaflet morphological information from cadaveric analyses, and constitutive parameters from mitral valves [16] to develop a model of an isolated tricuspid valve. Using the finite element method to solve for leaflet deformation and stresses provided transvalvular pressure and kinematic boundary conditions assigned to the annulus, they found that the motion and stresses of the tricuspid leaflets are "almost insensitive" to the leaflet constitutive model. Stress peaks were found in the anterior and septal leaflets close to the annulus. Additionally, the authors reported mean circumferential leaflet stretches in the range of 1.11–1.25 for the anterior leaflet, 1.09–1.22 for the posterior leaflets, and 1.09–1.25 for the septal leaflet, depending on the hyperelastic leaflet material parameter choice. Thus, their leaflet stretch values are in a similar range to those reported by Khoiy et al., which were derived from an in vitro model.

## 3 Tricuspid Annulus

### *3.1 Morphology and Nomenclature*

Albeit not always referred to as a saddle, the tricuspid valve annulus, similar to the mitral annulus, has a distinct three-dimensional topology reminiscent of a saddle. High points at the antero-septal annulus and the postero-lateral segment of the annulus as well as low points at the postero-septal annulus and the anterior annulus yield this shape [17]. Its two-dimensional projection lacks the symmetry of the mitral annulus in that it shows a clear deviation from an oval. Anatomically, the tricuspid annulus is situated more apically than the mitral valve by a few millimeters [3].

## 3.2 In Vivo Studies

In contrast to the tricuspid leaflets, the tricuspid annulus has been explored in vivo in detail, both in humans and in animals. Magnetic resonance imaging and echocardiography have been used to characterize the shape of the tricuspid annulus and its dynamics in patients with and without tricuspid regurgitation [18–21]. One of the earliest reports on annular dynamics in a beating human heart dates back to Tei et al. who used 2D echocardiography [22]. More recently, Fukuda et al. used 3D echocardiography to report the shape of the annulus throughout the cardiac cycle also in humans [17]. They describe the annulus as having distinct peaks and valleys. However, they refrain from describing the annulus as "saddle-shaped." Furthermore, they found the annulus to undergo significant cinching throughout the cardiac cycle with the orifice area decreasing from diastole to systole by ~29% in healthy patients and ~22% in patients with tricuspid regurgitation. This reduction in area was driven by length changes in the tricuspid annulus of approximately 15% in healthy patients, and approximately 10% in patients with tricuspid regurgitation.

The most common animal model used in the study of tricuspid annular dynamics is sheep. Hiro et al. were the first to implant sonomicrometry crystals on the tricuspid annulus of sheep and to record their locations in the beating heart [15]. They found that the mean tricuspid valve orifice area changes dynamically by 21.3% throughout the cardiac cycle. Fawzy et al. performed a similar analysis also using sonomicrometry crystals in sheep [23]. However, care must be taken, because their reported values for annular area differ by a factor of five from both Hiro et al. and Malinowski et al., who confirmed Hiro's findings [24]. Malinowski et al. also investigated the dynamics of the ovine tricuspid annulus under acute pulmonary hypertension and found that acute pulmonary hypertension lengthens the tricuspid valve annulus by 12% and reduces annular contractility locally. Additionally, they studied the effect of acute left ventricular mechanical unloading on tricuspid annular shape and dynamics but found little effect [25].

Lastly, Rausch et al. reanalyzed data by Malinowski et al. on the normal dynamics of the ovine tricuspid annulus employing mechanical metrics strain and curvature [26]. They found that strain and curvature change significantly throughout the cardiac cycle with focal minima and maxima of both metrics driving the dynamics of the annulus.

## 3.3 In Vitro Studies

Few data are available on the in vitro mechanics of the tricuspid annulus, likely due to the abundance of in vivo data. An exception are the studies by Basu et al. [27, 28]. In their first study, they used an intricate experimental setup to measure "annulus tension" in isolated porcine tricuspid valves. Specifically, they attached 10 wires to the annulus, each radially connecting to a surrounding force transducer.

In this configuration, they placed isolated porcine tricuspid valves in a right heart simulator. Pressurizing the valve to a systolic pressure of 40 mmHg, they measured wire forces and calculated annulus tension (wire force divided by annulus segment length) under three configurations: (1) normal, (2) papillary muscles displaced (15 mm) and annulus dilated (70%), and (3) after "clover" repair [29]. The study concluded that papillary muscle displacement and annular dilation increases annulus tension fourfold, implying that disease-induced annular forces may counteract and "decelerate" pathological annular dilation in patients. Additionally, they found that clover repair does not further impact annulus tension and therefore would not aid in reverse remodeling in patients. In their second study, Basu et al. investigated the mechanical properties and histological composition of the isolated porcine annulus. To this end, they explanted tricuspid valves, isolated the annular tissue, and divided it into anterior, posterior, and septal regions. Subsequently, they performed uniaxial tensile tests and histological tests on each region. They found that the septal annulus in pigs is the stiffest, likely due to high collagen contents, followed by the posterior, and, lastly, the anterior annulus.

Moreover, Adkins et al. studied the suture force necessary to cinch the dilated tricuspid annulus in an in vitro heart preparation, where dilation was achieved via phenol injection [30]. The authors found that phenol injection increases tricuspid annular area by 8.82% in vitro. The mean suture force necessary to reestablish normal valve area in the pressurized heart was measured to be 0.03 N.

### *3.4 In Silico Studies*

To the best of our knowledge no numerical studies exist that focus on the tricuspid annulus alone.

## 4 Tricuspid Chordae Tendineae

### *4.1 Morphology and Nomenclature*

The chordae tendineae insert into the leaflets' free-edge, rough zone, clear zone, and the basal region, and are classified accordingly. Silver et al. identifies additional "fan-like" chordae which insert into the commissural regions between leaflets. In contrast to the mitral chordae, the tricuspid chordae are generally less well organized and form complex networks connecting the leaflets to insertion sites on the endocardial wall, which are often distinct from either of the three papillary muscle heads [3, 31, 32].

## 4.2 In Vivo Studies

Similar to the tricuspid leaflets, there are currently few data available on the in vivo mechanics of the tricuspid chordae tendineae likely due to the challenges of imaging small anatomic details in a dynamic environment. One exception is the study by Fawzy et al. who implanted sonomicrometry crystals in sheep on the tips of the papillary muscles as well as the free edge of each leaflet. From these crystal pairs, they determine that the mean peak chordal deformation in the beating heart is 14%, 16.9%, and 5.2% for the anterior, posterior, and septal chordae, respectively.

## 4.3 In Vitro Studies

The most complete investigation of the in vitro mechanical properties of chordae tendineae goes back to Lim [31]. They performed uniaxial tensile tests on human tricuspid chordae tendineae from three patients (58+ years). Additionally, they performed "ultrastructural" analyses via scanning and transmission electron microscopy. From the uniaxial tensile test data, they derived that chordae tendineae follow the classic nonlinear stress-strain behavior observed in many other collagenous tissues with a linear pre-toe region, a transition region, and a linear post-transition region [33]. They suggested that tricuspid chordae tendineae are less extensible than those of the mitral valve. They attributed this difference to observed variations in the ultrastructure of the chordae, namely different collagen fibril diameters, different collagen fibril density, and different percentage of cross-sectional area covered by collagen fibrils. However, it must be noted that a subsequent study by the same authors performed the same analyses on a different subset of tricuspid chordae and found elastic properties that varied significantly from above findings [32]. Thus, care must be taken when interpreting either findings.

## 4.4 In Silico Studies

Although we are not aware of any numerical studies solely focusing on tricuspid chordae tendineae, Stevanella et al. reported papillary muscle reaction forces (the sum of all chordal forces for each papillary muscle) and force ranges for classes of chordae in their finite element study of the isolated tricuspid valve [14]. They found that reaction forces are similar between anterior, posterior, and septal papillary muscles and invariant to leaflet material models (<1 N). Additionally, they found that "marginal" chordae experience higher forces than "second order" chordae by a factor of approximately three.

## 5 Most Recent Studies

After submission of this chapter, a number of pertinent papers were published, which we briefly list here for completeness. Jett et al. [34] published a comprehensive in vitro study on the anisotropic mechanical properties and anatomical structure of porcine atrioventricular heart valve tissue. Moreover, Khoiy et al. [35] expanded on their previous work on the mechanical behavior of tricuspid leaflet mechanical properties and informed a hyperelastic constitutive law of the same tissue. On the modeling side, Kong et al. [36] developed detailed finite element models of human tricuspid valves based on computed tomography data and studied in vivo leaflet stress. Rausch et al. [37] used a sonomicrometry-based approach to delineate the in vivo mechanics of the tricuspid annulus under acute pulmonary hypertension, while Malinowski et al. [38] used the same technique to study tricuspid annular dynamics in explant, beating human hearts. Finally, Madukauwa-David et al. [39] investigated in vitro the effect of collagen content in human tricuspid annuli on suture dehiscence.

## 6 Conclusion

Although in the past decade significant effort has been invested into elucidating the biomechanics of the tricuspid valve, our understanding of the forgotten valve is still lacking behind that of the mitral valve. After reviewing the existing literature, we identify three areas of research that we believe require more attention: (1) in vivo studies of the tricuspid leaflet and chordae mechanics, (2) in silico studies of tricuspid leaflets, annulus, and chordae, and (3) studies of the remodeling potential of the tricuspid valve that are currently absent. Future studies will hopefully fill these gaps in our knowledge and bring us closer to a more complete understanding of the tricuspid valve that may translate into better clinical management of tricuspid regurgitation.

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